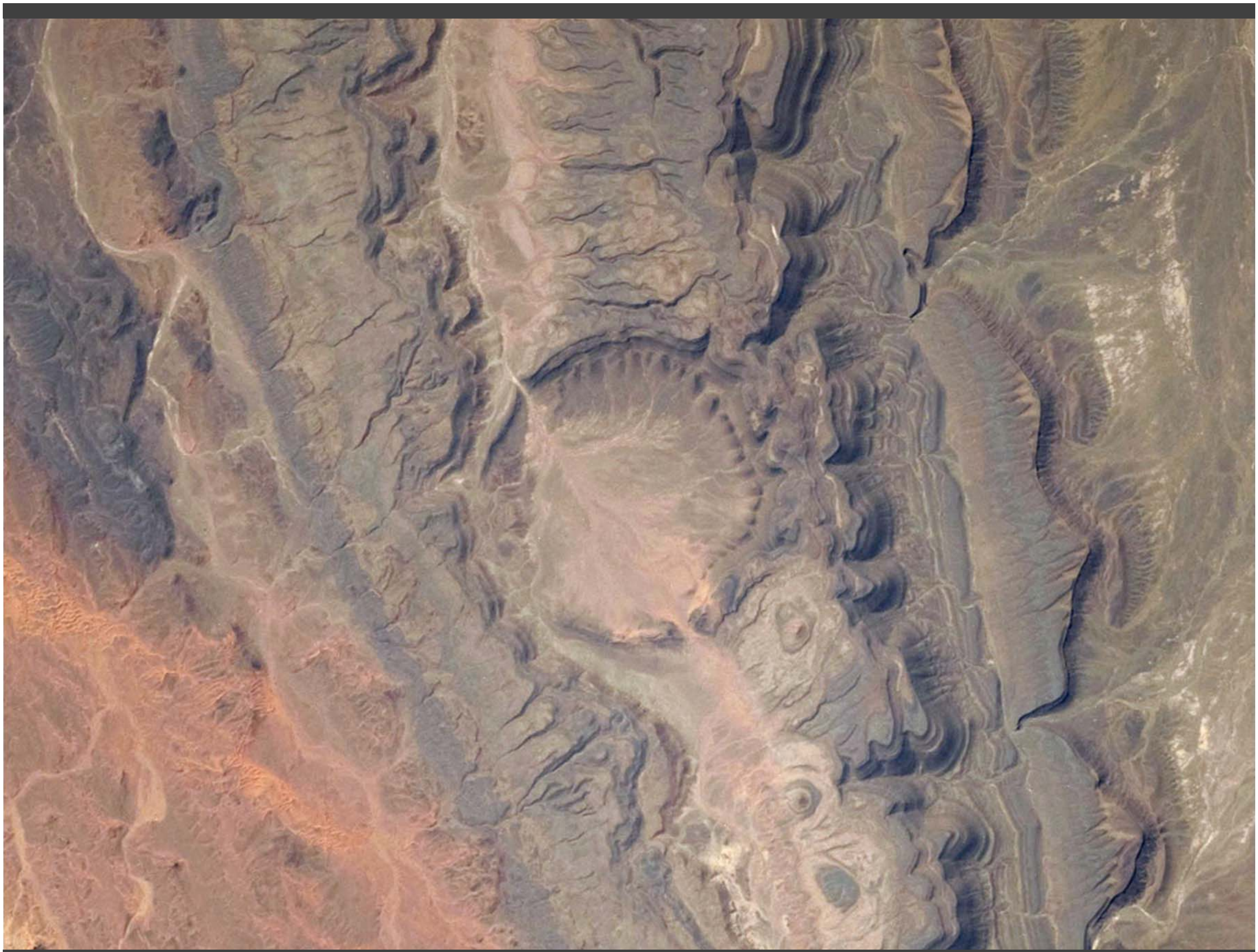
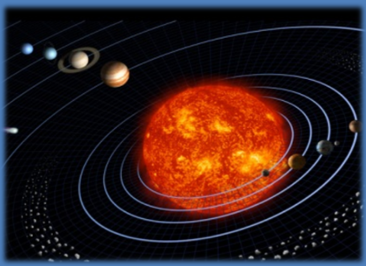
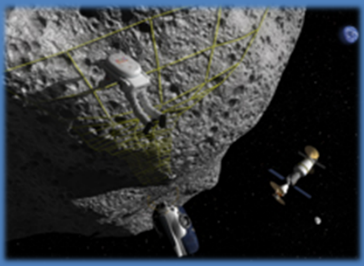
National Aeronautics and
Space Administration

CRATER COMPARISONS

Investigating Impact Craters on Earth and Other Planetary Worlds







STUDENT GUIDE

CRATER COMPARISONS

Investigating Impact Craters on Earth and Other Planetary Worlds

STUDENT GUIDE

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CRATER COMPARISONS

Investigating Impact Craters on Earth and Other Planetary Worlds

PART 1: OBSERVATIONS AND PRELIMINARY QUESTIONS

The images below are of impact craters from different planetary worlds in our Solar System. In the table below, list your observations of similarities and differences of the visible characteristics of these craters.

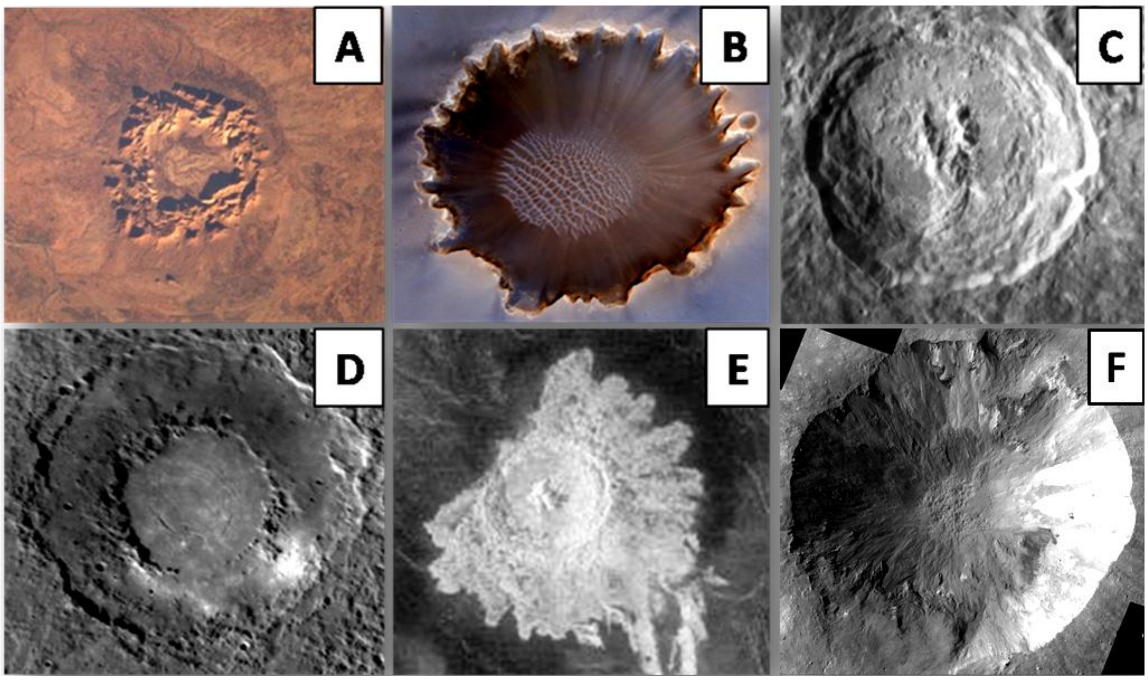


Image Credit: NASA

SIMILARITIES	DIFFERENCES

Based on your observations of the above images, list at least 1 question you have about impact craters in the space below?

PART 2: EXPLORING IMPACT CRATERS AND LOGGING INITIAL OBSERVATIONS

BACKGROUND INFORMATION

A. Causes of Impacts

Impact craters are features created on the surface of a planetary body when a meteoroid strikes the surface creating a bowl-shaped hole. Meteoroids can be particles of cosmic dust, parts of asteroids, planets, moons, leftover material from the formation of our Solar System, or even comets – objects made of rock and ice that travel through our Solar System. Small meteoroids burn up in our atmosphere. Those that are large enough to make it through the atmosphere, strike the surface creating an impact crater. The number and sizes of impact craters found on the surface of a planetary world varies. Fragments of asteroids and other planets are the most common objects that are the meteorites we find on Earth.

Meteoroid: A chunk of rock or ice orbiting the Sun inside the Solar System.

Meteor: What we see when a meteoroid attempts to pass through Earth's atmosphere and burns up.

Meteorite: Left over material that survives the trip through the atmosphere and is found on the surface.

Believe it or not, you have probably seen hundreds of impact craters! Every time you look up at the Moon you are looking at evidence of ancient collisions in our Solar System. Impact craters are found on almost all of the rocky (terrestrial) planetary worlds (including planets, moons, and asteroids) in our Solar System. The impact process is the most common geologic process seen across our Solar System.

B. Formation of Craters

There are three main stages involved in the formation of craters:

- **Contact/compression stage:** A meteor (a meteoroid that has successfully made it through our atmosphere) traveling 10-15 kilometers per second strikes the surface of a planet. As it strikes, shock waves compress the surface and cause rocky material to almost liquefy or melt.

- **Excavation stage:** Material gets ejected or thrown out of the newly formed hole in the ground.

- **Modification stage:** The ejecta settles out onto the surface and material in the walls of the newly formed crater slump. (Slump is when material moves a short distance down a slope.)

The entire crater formation process occurs in seconds. Usually much of the meteoroid is vaporized. Fragments that remain are called meteorites. The final crater will continue to be modified by gravity and erosion.

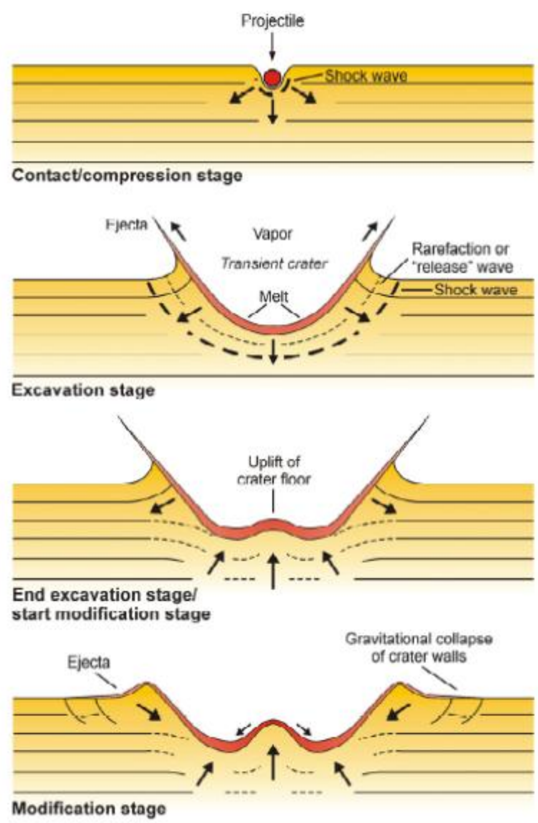
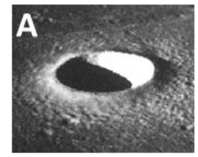


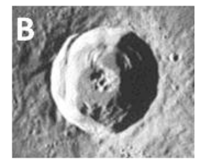
Image Credit: Planetary Science Institute

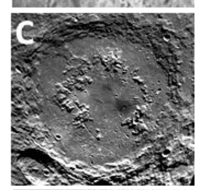
C. Crater Characteristics

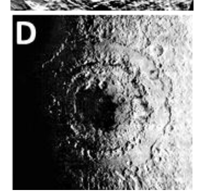
There are 5 main parts or physical characteristics of a crater. These include:

- **Rim:** The raised area around the edge of the crater
- **Wall:** The sides of the crater
- **Floor:** The bottom of the crater
- **Central peak:** An uplifted mound in the floor of the crater
- **Ejecta:** Material from inside the crater that is thrown out during the impact event. Ejecta can appear as rays or as a blanket of material surrounding the crater.









There are two general types of craters:

1. **Simple Crater:** (Crater A shown on the right)
   - Simple bowl shape
   - Generally smaller and younger than complex craters.

2. **Complex Crater:** (Craters B, C, and D shown on the right)
   - Much larger and older than simple craters.
   - Frequently has a central peak (B). This peak is created when melted rock rebounds or gets uplifted during the impact event and then solidifies in that uplifted position.
   - The larger the impact crater, the more complex it is.
   - Some very large complex craters have what appears as a ring of peaks (C) or can even have a multi-ring structure (D). These very large complex craters are sometimes referred to as impact basins.
   - Additional characteristics include material that has slumped along the walls giving them a terraced, step-like, or inner ring appearance.

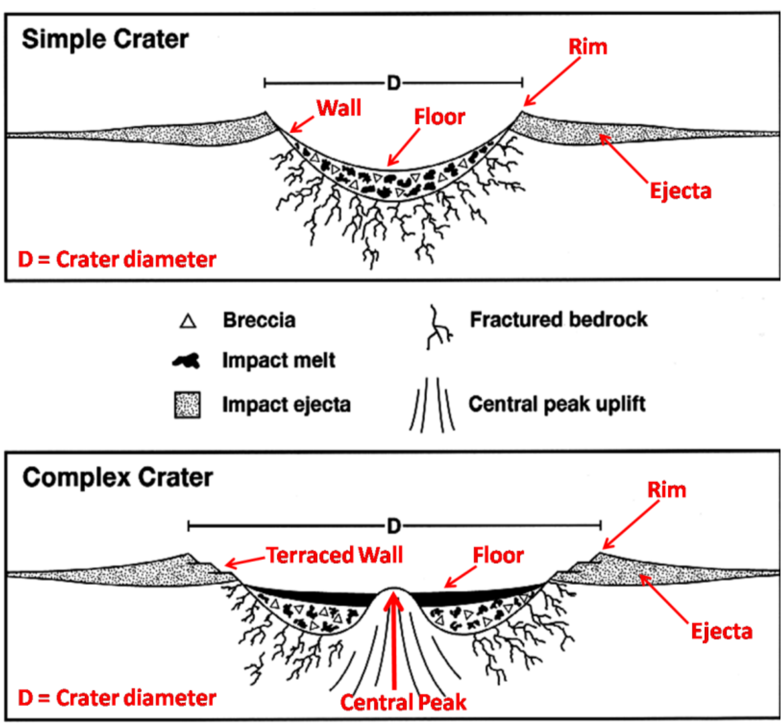


Image Credit: NASA/GSFC

D. Using Craters to Reveal the Geologic History of a Surface

Impact craters and their physical characteristics open up a window into a planetary world's history and geology. Once a crater is formed, making observations of how it is modified or eroded tells us a lot about that planetary world. Craters can be modified by wind, water, tectonics, volcanic processes, or even other impacts. As part of these processes and others, craters can be covered or filled in by water, lava, sediments (sand, dust, etc), landslides, vegetation, or even ejecta from other craters.

When scientists examine the surfaces of planetary worlds, it is common for them to use relative terms for age dating. They will often refer to a surface as being *older* or *younger* relative to another. Additionally, they often refer to a process as having occurred *recently* or *long ago*. In geologic terms, *recent* may be 50,000 years ago, especially if you consider the Solar System as being 4.6 billion years old.

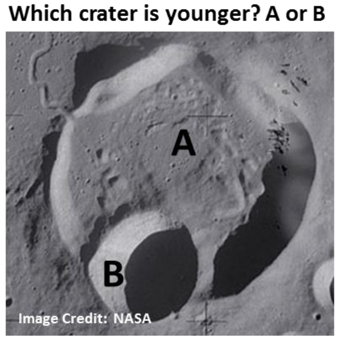
When looking at planetary surfaces, a *younger* surface is considered one that has been *recently* resurfaced by some process (wind, water, volcanics, or some other process). An *older* surface is one that has NOT been resurfaced by any process in a *long* time. Think of it this way…consider the street in front of your house. Over time, the street will become worn and will likely crack and even get pot holes. With every passing day, the street "ages". One day, the street gets repaved. That resurfaced street, if we think in relative terms, is now *younger*. The older street is still there – it is now under the newer surface. This works in a similar way with planets. A planet may be 4.6 billion years old, but if a volcano erupts lava onto the surface, that lava can fill in craters or even cover them up completely. That 4.6 billion year old surface basically just got "repaved" and this new surface is younger, with the older terrain underneath.

Geologic Principles

Scientists use geologic principles or rules to help determine relative ages. By applying these rules you can gain insight into the sequence of geologic events that took place in a region. Three of these principles include:

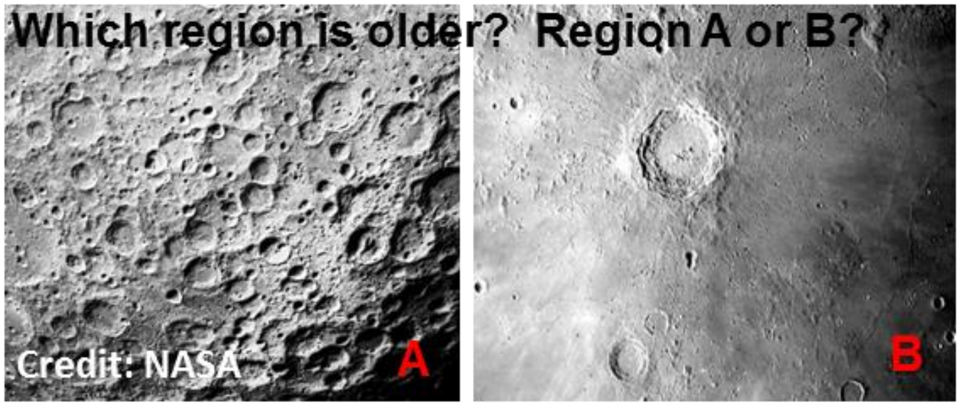
1. *Principle of Superposition:*
    - The order of layers or geologic features found on the surface provides information about which features are older or younger.
    - Features found on top are the youngest.
    - Relating to craters, if a crater is found on the floor of or overlapping the rim of another crater it must be younger. The crater on the bottom must have been there first, making it older.

Which crater is younger? A or B



Answers: Layer A is younger; Crater B is younger.

2. *Crater Density:* The more craters on the surface of a planet, the older that surface is.



Answer: Region A is older.

3. *Crater Classification:* The more modified a crater, the older it is. The relative ages of craters can be determined by classifying them into one of the following categories:
   - **<u>Preserved Craters:</u>** Youngest, best preserved craters
     - Circular craters
     - Raised rim
     - Look fresh
     - Can sometimes see ejecta blanket or rays of ejecta

   - **<u>Modified Craters:</u>** Middle aged craters with evidence of modification
     - Can be modified or eroded by wind, water, lava, or some other process
     - Can vary from being slightly to severely modified
     - Floor may be partially filled in with sediment
     - Rim may appear uneven or somewhat irregular in shape

   - **<u>Destroyed Craters:</u>** Oldest craters that have been severely altered
     - Appear very flat and very worn away (severely eroded)
     - Broken rims
     - Almost completely filled in by sediment, lava, or other material.

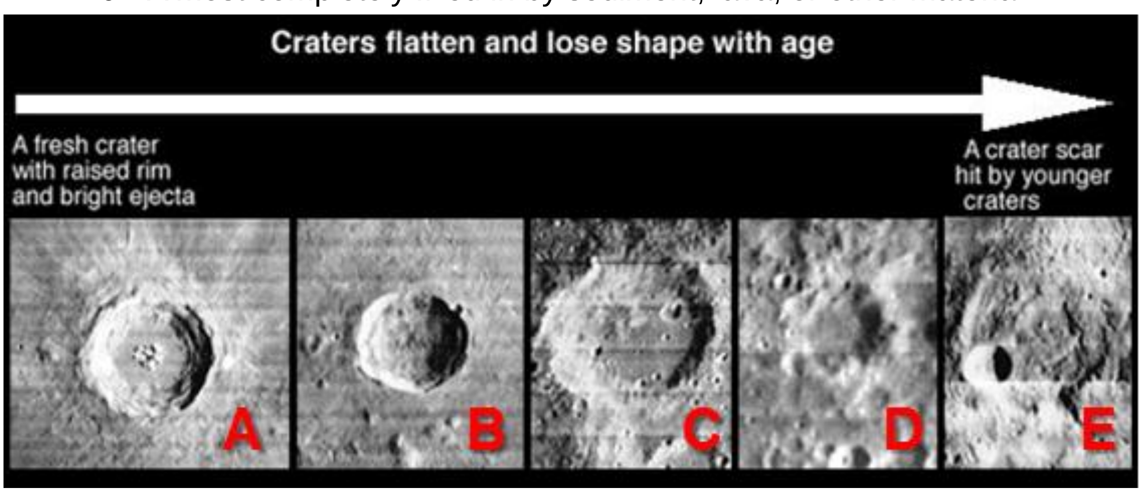


Image Credit: Planetary Science

E. Geologic History Practice Scenarios

Let's see if you can apply some of these geologic principles to help make inferences about the geologic history of a set of planetary worlds. Discuss the scenarios below. Be sure to justify your answer with evidence supported by the above geologic rules.

SCENARIO #1

- PLANET #1: This planet has few impact craters. Craters range in size from relatively small (~1 km) to large craters (~50 km). Most craters are severely modified.

- PLANET #2: This planet has many impact craters. Craters range in size from relatively small (~1 km) to very large craters (~100+ km). Smaller craters have raised rims and look preserved. Most of the larger craters are modified or destroyed.

Question 1: Which planetary surface is older? Explain.
Answer: *The surface of Planet 2 is older than Planet 1.*

- *Supporting evidence: We can base this on the observed number of impact craters on the surface. We can infer Planet 2 has more craters on the surface of the planet overall. Crater density tells us more craters = older surface. Additionally, larger craters are generally more complex and older than smaller simple craters.*

Question 2*:* What can you infer about the processes affecting these planets? Explain.
Answer:

- *Planet 1 must have active processes eroding the surface. This can be inferred because most craters are modified.*
- *Planet 2 has preserved, modified, and destroyed craters. Since the larger craters on Planet 2 are modified or destroyed, this may indicate that early in the history of this planet, there were indeed active processes. As the newer/younger craters are preserved craters, these are younger craters that must have formed on the surface once those active processes no longer existed.*

SCENARIO #2

- PLANET #1: This planet has many impact craters. Craters range in size from ~20 to ~40 km. Most craters are modified. Surface appears to be rugged (not very smooth).

- PLANET #2: This planet has many impact craters. Craters range in size from relatively small (~1 km) to very large craters (~100+ km). Most of the craters are modified. Surface appears rugged; sand dunes are visible in some areas.

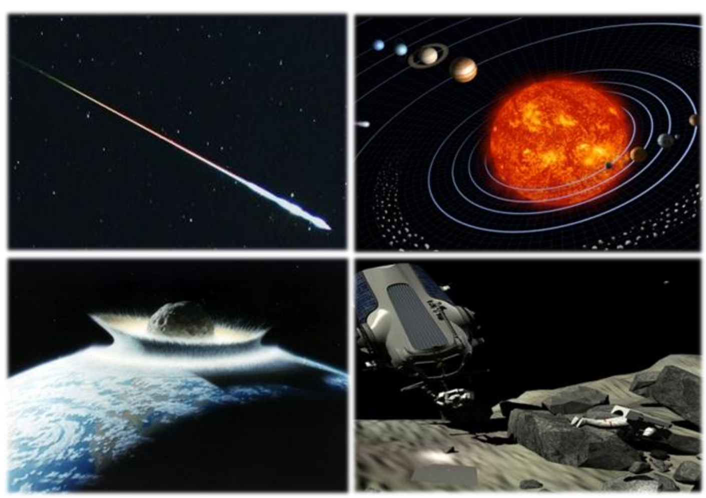
Question 1: Which planetary surface is older? Explain.
Answer: *This is a tricky one as this scenario indicated that both planets have numerous impact craters. You could assume these planetary surfaces are about the same age (unless you can clearly see that one has more craters than the other). You could also consider the size differences of the craters. In general, very large craters (~100+ km) are very old. As Planet 2 has larger craters, you could infer that the surface of Planet 2 is older.*

Question 2*:* What can you infer about the processes affecting these planets? Explain.
Answer:

- *There must have been some type of active processes affecting both of these planets as the craters observed are modified.*
- *The only observation stated for Planet 1 is that the surface appears to be rugged. This could infer that there were volcanic processes that may have affected the surface.*
- *Planet 2 has both rugged areas as well as sand dunes identified. This may indicate that both volcanic and wind processes have affected the surface.*
- *As the craters are modified (as opposed to destroyed), this perhaps tells us that the processes did not occur for a long enough period of time to further erode the craters. More information about the planet would help you better infer what process(es) may have affected a given planetary world.*

F. What Does It All Mean -- The Big Picture: What Can You Learn From Studying Impacts
Scientists apply these geologic principles (and others) to study impact craters which can help them learn about the history of our Solar System. As the impact process is one of the most dominant processes that has affected terrestrial worlds, craters help provide clues about how our Solar System has changed over time. Scientists can examine the relative ages of planetary surfaces and how the frequency of impacts and size of material that have struck the surfaces of planets has changed over time. Scientists also look for evidence of processes that may have modified craters such as wind, water, or volcanic processes. This helps them determine not only the types of processes that have shaped (or continue to shape) the surface of a planet but also provides clues as to when those processes may have occurred.

By comparing Earth to other planetary worlds (comparative planetology), scientists are able to use what they know and understand about Earth to better hypothesize and draw conclusions about other planetary worlds and our Solar System as a whole. Making detailed observations and looking for patterns is extremely important. Scientists combine their observations and apply the knowledge they have about a planetary world to interpret what those observations mean. Knowledge that can help provide additional insight includes the composition of the planetary world, temperatures, the atmosphere (if one exists), the interior, the surface features, etc. The more knowledge you have about a planetary world as a whole, the better you can draw conclusions about its history.



In thinking about the “big picture” and what it all means, by studying impact craters, you can: 1) better understand the history of our Solar System, 2) make predictions about potential future impacts, and 3) help uncover information that can help drive future robotic or even human exploration of other worlds. For both professional and student scientists conducting any investigation, it is important to always keep the big picture in mind.

PART 2: INITIAL OBSERVATIONS

Now that you have some background knowledge, let's look at the initial set of images from Part 1 of this activity. Crater images are of Earth (A), Mars (B), Earth's Moon (C), Mercury (D), Venus (E), and an asteroid named Vesta (F).

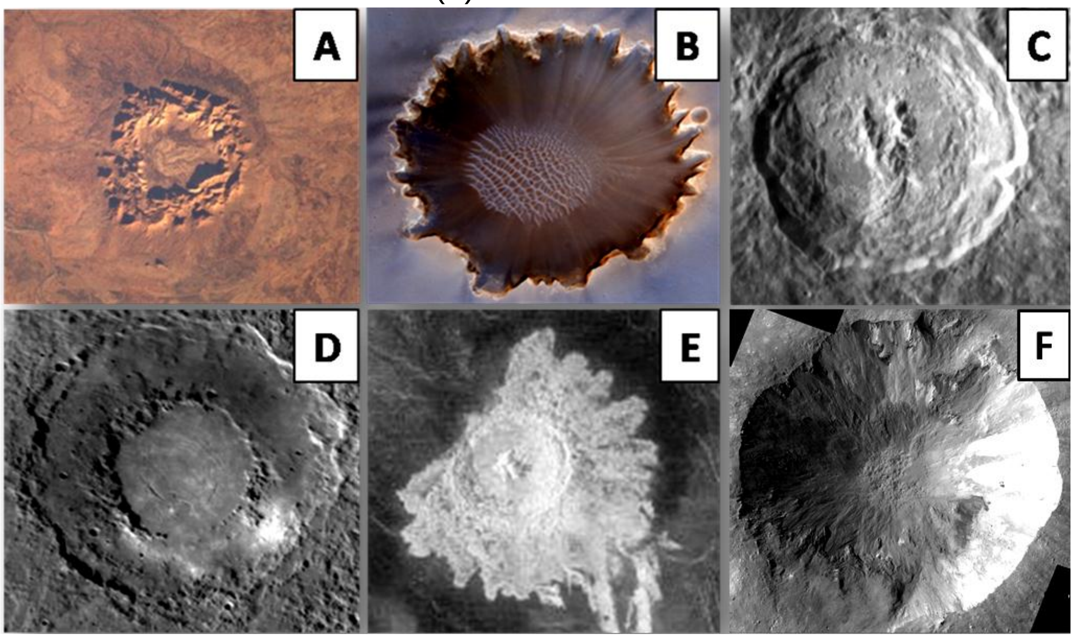


Image Credit: NASA

In the table below, use a check mark to select the characteristics that are visible in each crater:

	Image A	Image B	Image C	Image D	Image E	Image F
Visible rim						
Visible ejecta blanket						
Smooth flat floor						
Filled in or outlined by water						
Central Uplift						
Terraced Walls						

As you completed this exercise, did you want to list comments or give an explanation to help justify your selections? Being able to list miscellaneous notes can be very useful. You are encouraged to always have a place to list miscellaneous notes as you collect and log data.

Do you think you have enough data to answer the question: **What are the similarities and differences between the characteristics of craters on planets? What might these characteristics reveal about the geologic history of those worlds compared to Earth?** With just one image from each planet…definitely not. This activity will step you through an investigation to help you answer this question….and perhaps interest you to want to expand on this initial research.

This investigation will examine the geologic histories of different planetary worlds through a comparison of crater characteristics. It will therefore be important to gather a consistent set of data from different planetary bodies. Some of you will focus on images of Earth, Mars, Earth's Moon, or some other world. As your research comes together, it will be essential to share your findings with the class. Let's continue to explore and investigate…

PART 3: CONTINUING OUR CRATER INVESTIGATION

As you work through this investigation, you are actually modeling skills and practices used by professional scientists. The image below is an illustration of the process of science. Scientists use this process when conducting investigations.

You have already started completing this process. You have asked a preliminary question (Step 1), made initial observations (Step 2), and gained background knowledge (Step 3) about craters.

Other steps you will complete include:

- Step 4: Creating an Experiment Design
- Step 5: Collecting and Compiling Data
- Step 6: Displaying Data
- Step 7: Analyzing and Interpreting Data
- Step 8: Drawing Conclusions
- Step 9: Sharing Research
  (Once your investigation is complete, consider who you might present your research to.)

At this point, we are ready to move into Step 4, creating an experiment design. An experiment design is a plan or the methods (procedure) you will use to conduct your research. Creating a solid plan is extremely important as it will allow you to consistently collect and compile data. It is important to have the same data to compare one planetary world to another. If you have consistent data collected for each planetary world you investigate, you will be better prepared to display, analyze, and interpret that data in order to draw conclusions.

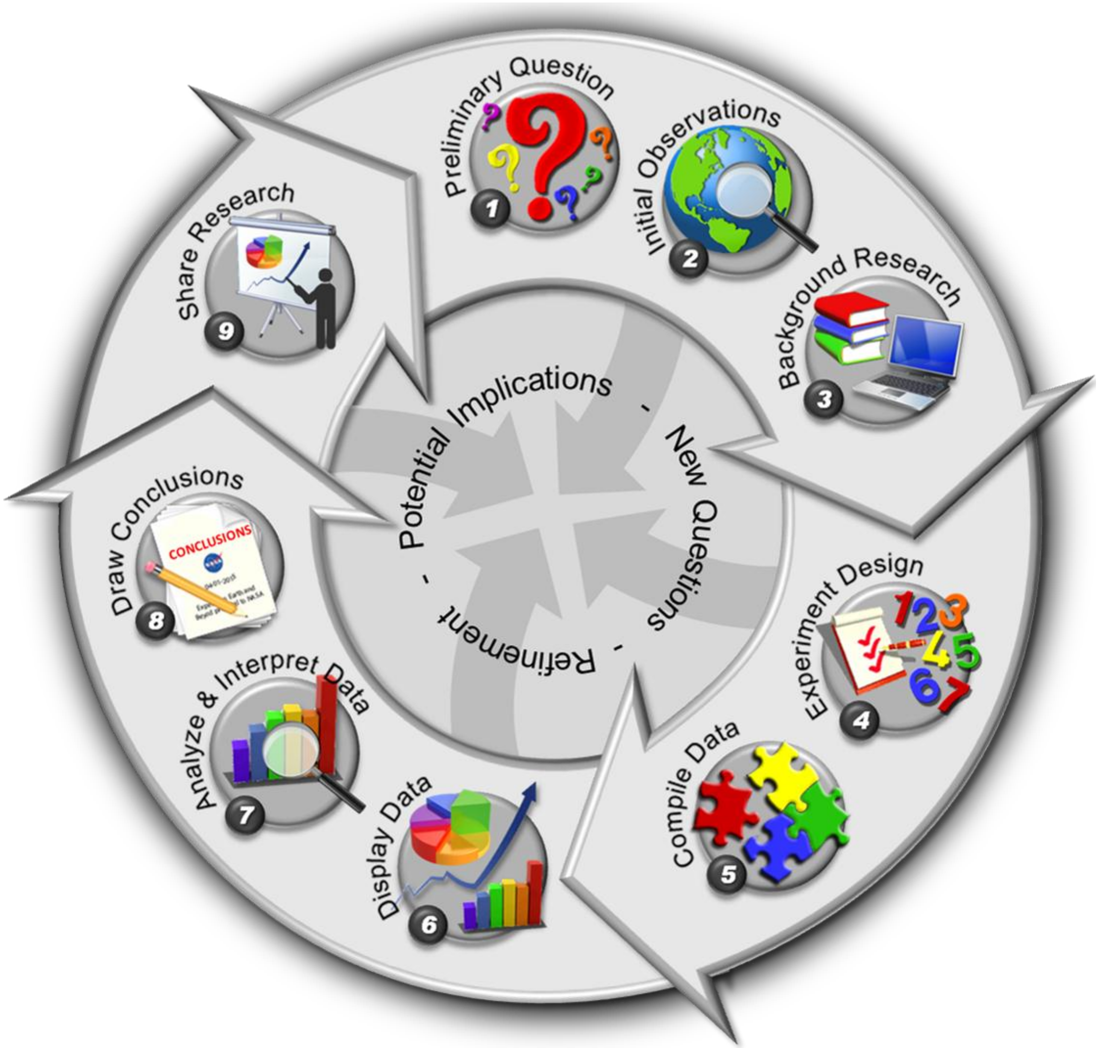


Image Credit: NASA/JSC/ARES/EEAB

PROCESS OF SCIENCE STEP 4: Experiment Design

The very first part of this step is to list your finalized research question. As you work through the first three steps of the process of science, you may find that as you gain more knowledge you may tweak or refine your question. By the time you are creating your experiment design, your question should be finalized. To help ensure this investigation can be successfully completed, a finalized research question has been created and is listed below. You will notice there are two questions listed as the **Research Question**. This simply allows the research to be broken down into two parts. First, you will compare and contrast crater characteristics on different planetary worlds. Secondly, this will allow you to make a determination about the geologic history of these worlds compared to Earth.

The next part of this step is to list your current hypothesis/es. A hypothesis can be thought of as an educated guess. Ideally, a hypothesis should reflect your current understanding based on the patterns you have observed in preliminary images and background knowledge you may have. Again, to help guide your research, a set of hypothesis statements have been created. Each hypothesis statement is related to the physical characteristics of craters discussed earlier (central peak, rim, walls, ejecta) as well as crater sizes and classifications.

Research Question: What are the similarities and differences between the characteristics of craters on different planetary worlds? What might these characteristics reveal about the geologic history of those worlds compared to Earth?

Hypothesis: Based on the images we have observed so far, and what we know about impact craters in our Solar System, we hypothesize that…..

- Earth craters will be *smaller, larger, or the same size* compared to craters on other planetary worlds.
- Earth craters will more often *have or not have* a central peak compared to craters on other planetary worlds.
- Earth craters will have a *more or less* defined rim compared to craters on other planetary worlds.
- Earth craters will have *smoother or more terraced* walls compared to craters on other planetary worlds.
- Earth craters will more often be *preserved, modified, or destroyed* compared to craters on other worlds.
- Earth craters will *more often or less often* have visible ejecta blankets compared to craters on other worlds.

Perhaps the most challenging part of an experiment design is determining the specific details of your plan. This includes what data you will collect, what specific data you will log, how many images you will strive to look at, what measurements you will make (and how you will make them), the sources you will use to find data, and more! Below is a list of research considerations (and how they are addressed) that were taken into account in order to help you answer the listed science question and determine if your hypothesis statements are supported or refuted.

RESEARCH CONSIDERATIONS:

1. **Image Data Collection:** For this investigation, you will use Crew Earth Observation (CEO) Imagery of Earth provided in the *Crater Comparison* activity. Images were retrieved from the Gateway to Astronaut Photography of Earth website. Additional data/information was retrieved from the Earth Impact Database website.
2. **Specific Data to Collect:** The following information will be logged from each image:
   1) Image Identification #; 2) Crater name (if known); 3) Latitude (N); 4) Longitude (E); 5) Planetary Body; 6) Geographic location (country or region)
   Additional data that focus on visible observations include: 7) Crater diameter (km); 8) Central Peak (yes, no, unsure); 9) Crater Walls (smooth, terraced, none visible, not clear); 10) Rim Definition (distinctly raised, somewhat raised, barely raised, not visible); [Not visible = filled in with water or completed eroded]; 11) Crater Classification (preserved, modified, destroyed); 12) Visible Ejecta (yes, no, unsure); 13) Miscellaneous notes or observations; 14) Sketches of craters.
3. **Number of Images:** Log data of 8 different craters on Earth and 8 different craters from each planetary world (minimum).
4. **Geographic Regions:** This investigation will not focus on any particular region.
5. **Other Data Sets:** For this investigation, you will use images of other planetary worlds provided in this *Crater Comparison* activity. Images were retrieved from the JPL Planetary Photojournal website and other NASA websites.
6. **Measurements:** You can make estimated measurements of craters based on scale bars or measurement lines provided.
7. **Sources:** Gateway to Astronaut Photography of Earth (http://eol.jsc.nasa.gov); Earth Impact Database (http://www.passc.net/EarthImpactDatabase/index.html); JPL Planetary Photojournal (http://photojournal.jpl.nasa.gov/).

It is important to log your data consistently. Notice on the data table sample provided (next page), the column headings provide specific details as to the information you should log. For example, the column heading for crater diameter states "**Crater Diameter (km)**". By including (km) in the column title, it signifies that all diameters logged are in km. As you log the diameter of each crater, only include the diameter measured. Do not include *km* with each entry. This will allow you to more easily sort information on a spreadsheet if desired.

The details listed for the visible observations are very specific details that will also allow you to make common comparisons among craters on Earth and other planetary worlds. If you wish to make additions or changes to any of those details, feel free to do so. Just make sure you collect a consistent set of data for all planetary worlds.

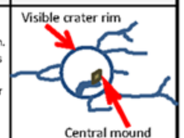
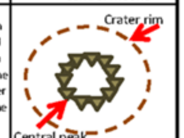
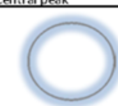
The remaining steps of this investigation include: Step 5: Collect and Compile Data; Step 6: Display Data; Step 7: Analyze & Interpret Data; and Step 8: Draw Conclusions.

PROCESS OF SCIENCE STEP 5: Collect and Compile Data

Shown below are a data table for craters on Earth and an additional data table to be used for observations of craters on other planetary worlds. As this research involves comparing craters on Earth with other planetary worlds, the same table headings are provided on both tables. This will allow you to make consistent comparisons of your data.

DATA TABLE - CRATERS ON EARTH

Please note that latitudes are provided as North latitudes [Latitude (N)]. A latitude with a (-) is a South latitude: Example: -27.8 is the same as 27.8S.
Also note that longitudes are provided as East longitudes [Longitude (E)]. A longitude with a (-) is a West longitude: Example: -68.5 is the same as 68.5W.

Image Identification #	Crater Name *(if known)*	Latitude (N)	Longitude (E)	Planetary Body	Geographic location *(country or region)*	Crater Diameter (km)	Central Peak *Yes (Y), No (N), Unsure (U)*	Crater Walls *(smooth, terraced, none visible, not clear)*	Rim Definition *(distinctly raised, somewhat raised, barely raised, not visible) Not visible = filled in with water or completed eroded*	Crater Classification *(preserved, modified, destroyed)*	Visible Ejecta Blanket Yes (Y), No (N), Unsure (U)	Miscellaneous notes or observations	Sketch(es) of Craters *(optional)*
ISS012-E-15881	Manicoua-gan	51.5	-68.5	Earth	Canada	51	Y	not clear	not visible	modified	N	Original diameter of crater ~100km. After erosion about 51km remains visible. "Arms"/rivers extend out from the rim. Central mound near cent/right of crater.	
ISS015-E-17360	Gosses Bluff	-23.9	132.3	Earth	Australia	15	Y	none visible ★	barely visible	modified	N	According to information research about this crater, the well defined bumpy circular feature is part of a central uplift. If you look closely, the rim is barely visible as a faded outer rim. This barely visible outline is the identified crater diameter.	
ISS018-E-14908	Tenoumer	22.9	-10.4	Earth	Mauritania	1.9	N	smooth	somewhat raised	modified	U	The rim of this crater looks soft. The left side in the image appears as though it is more eroded than the right side. There looks to be evidence of eroded ejecta around the rim.	

DATA TABLE - CRATERS ON ____________________

Image Identification #	Crater Name *(if known)*	Latitude (N)	Longitude (E)	Planetary Body	Geographic location	Crater Diameter (km)	Central Peak *Yes (Y), No (N), Unsure (U)*	Crater Walls *(smooth, terraced, none visible, not clear)*	Rim Definition *(distinctly raised, somewhat raised, barely raised, not visible) Not visible = filled in with water or completed eroded*	Crater Classification *(preserved, modified, destroyed)*	Visible Ejecta Blanket Yes (Y), No (N), Unsure (U)	Miscellaneous notes or observations	Sketch(es) of Craters *(optional)*

As you log your observations, be sure to be as consistent as possible. If you are able to create a spreadsheet on a computer to log your data, this will allow you to more easily display your data in the next step.

The first six columns on the data tables are considered **metadata**. This is standard information from the images/data you are observing. This includes the image identification number, the name of the crater (if known), the latitude, longitude, planetary body name, and the geographic location.

The remaining columns of information include your observations of the crater(s) in each image. As previously mentioned, by having specific and consistent choices/considerations, you will be able to make consistent comparisons of your observations of craters on Earth and other planetary worlds.

★ *The walls of this crater have been completely eroded. Only the central peak is visible.*

PROCESS OF SCIENCE STEP 6: Display Data

After you finish collecting and compiling data from at least 8 craters for each planetary world, it is time to display that data so you can make observations and later analyze the data. The three parts of Step 6 are to: 1) **Decide how to display your data** (Sorted Data Table(s), Graphs, Maps, Image Illustrations); 2) **Create your data displays**; and 3) **List observations**. As you create your own data displays, be sure to list 2-3 observations of each display. Use the samples provided as examples.

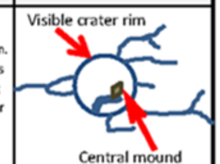
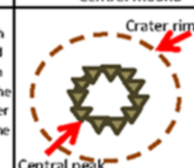
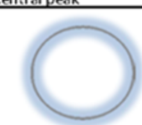
DATA TABLES

Your completed or master data table provides you with very useful information. Sorting your data is important as it allows you to look for patterns. Remember, with each data display be sure to list 2-3 observations.

The sample table below has been sorted by *crater diameter.* Observations have been listed below the table.

DATA TABLE - CRATERS ON EARTH

Please note that latitudes are provided as North latitudes [Latitude (N)]. A latitude with a (-) is a South latitude: Example: -27.8 is the same as 27.8S.
Also note that longitudes are provided as East longitudes [Longitude (E)]. A longitude with a (-) is a West longitude: Example: -68.5 is the same as 68.5W.

Image Identification #	Crater Name *(if known)*	Latitude (N)	Longitude (E)	Planetary Body	Geographic location *(country or region)*	Crater Diameter (km)	Central Peak *Yes (Y), No (N), Unsure (U)*	Crater Walls *(smooth, terraced, none visible, not clear)*	Rim Definition *(distinctly raised, somewhat raised, barely raised, not visible) Not visible = filled in with water or completed eroded*	Crater Classification *(preserved, modified, destroyed)*	Visible Ejecta Blanket *Yes (Y), No (N), Unsure (U)*	Miscellaneous notes or observations	Sketch(es) of Craters *(optional)*
ISS012-E-15881	Manicoua-gan	51.5	-68.5	Earth	Canada	51	Y	not clear	not visible	modified	N	Original diameter of crater ~100km. After erosion about 51km remains visible. "Arms"/rivers extend out from the rim. Central mound near cent/right of crater.	
ISS015-E-17360	Gosses Bluff	-23.9	132.3	Earth	Australia	15	Y	none visible	barely visible	modified	N	According to information research about this crater, the well defined bumpy circular feature is part of a central uplift. If you look closely, the rim is barely visible as a faded outer rim. This barely visible outline is the identified crater diameter.	
ISS018-E-14908	Tenoumer	22.9	-10.4	Earth	Mauritania	1.9	N	smooth	somewhat raised	modified	U	The rim of this crater looks soft. The left side in the image appears as though it is more eroded than the right side. There looks to be evidence of eroded ejecta around the rim.	

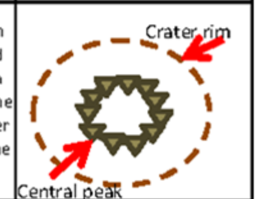
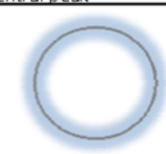
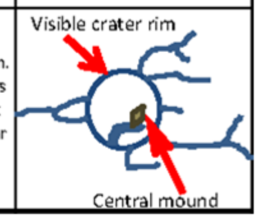
Observation #1: The larger the crater diameter, the less visible the rim definition.
Observation #2: There larger the crater diameter, the more likely it is for the crater to have a central uplift.
Observation #3: Craters with a diameter over 15km appear to have a central uplift.

NOTE:
- Observations should state general patterns or notable information the data display is illustrating.
- Observations **do not** attempt to decipher what those patterns mean.
- Observations should generally not be questionable. Everyone should be able to agree on stated observations.

This sample table was sorted by *latitude.* Observations have been listed below the table.

DATA TABLE - CRATERS ON EARTH

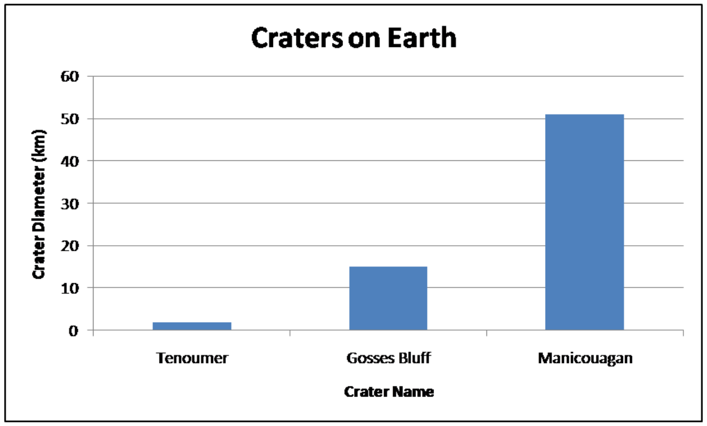
Please note that latitudes are provided as North latitudes [Latitude (N)]. A latitude with a (-) is a South latitude: Example: -27.8 is the same as 27.8S.
Also note that longitudes are provided as East longitudes [Longitude (E)]. A longitude with a (-) is a West longitude: Example: -68.5 is the same as 68.5W.

Image Identification #	**Crater Name** *(if known)*	**Latitude (N)**	**Longitude (E)**	**Planetary Body**	**Geographic location** *(country or region)*	**Crater Diameter (km)**	**Central Peak** *Yes (Y), No (N), Unsure (U)*	**Crater Walls** *(smooth, terraced, none visible, not clear)*	**Rim Definition** *(distinctly raised, somewhat raised, barely raised, not visible) Not visible = filled in with water or completed eroded*	**Crater Classification** *(preserved, modified, destroyed)*	**Visible Ejecta Blanket** *Yes (Y), No (N), Unsure (U)*	**Miscellaneous notes or observations**	**Sketch(es) of Craters** *(optional)*
ISS015-E-17360	Gosses Bluff	-23.9	132.3	Earth	Australia	15	Y	none visible	barely visible	modified	N	According to information research about this crater, the well defined bumpy circular feature is part of a central uplift. If you look closely, the rim is barely visible as a faded outer rim. This barely visible outline is the identified crater diameter.	
ISS018-E-14908	Tenoumer	22.9	-10.4	Earth	Mauritania	1.9	N	smooth	somewhat raised	modified	U	The rim of this crater looks soft. The left side in the image appears as though it is more eroded than the right side. There looks to be evidence of eroded ejecta around the rim.	
ISS012-E-15881	Manicoua-gan	51.5	-68.5	Earth	Canada	51	Y	not clear	not visible	modified	N	Original diameter of crater ~100km. After erosion about 51km remains visible. "Arms"/rivers extend out from the rim. Central mound near cent/right of crater.	

Observation #1: Craters located in both the southern and northern hemisphere of Earth are modified.
Observation #2: Craters located in both the southern and northern hemisphere of Earth have central uplifts.
Observation #3: Ejecta blankets are not easily detected in craters located in either hemisphere.

GRAPHS

Graphs can allow you to visualize and illustrate your data, again allowing you to look for patterns. The graph below is showing the diameters of different craters on Earth.



Observation #1: Crater diameters on Earth, based on those observed, range from ~2km to ~50km.

Observation #2: There are not many craters of similar sizes on Earth

Observation #3: The range of craters sizes on Earth is wide.

Note: The more data you graph, the easier it is to make observations and look for notable patterns.

MAPS

Maps can allow you look for local, regional, or global patterns. The map shown here indicates the global distribution of impact craters (referred to as structures) on Earth.

Observation #1: Impact Craters are located on *most* continents on Earth.

Observation #2: The craters we observed are in North America, Africa, and Australia.

Observation #3: There are no impact craters found in Greenland or Antarctica.

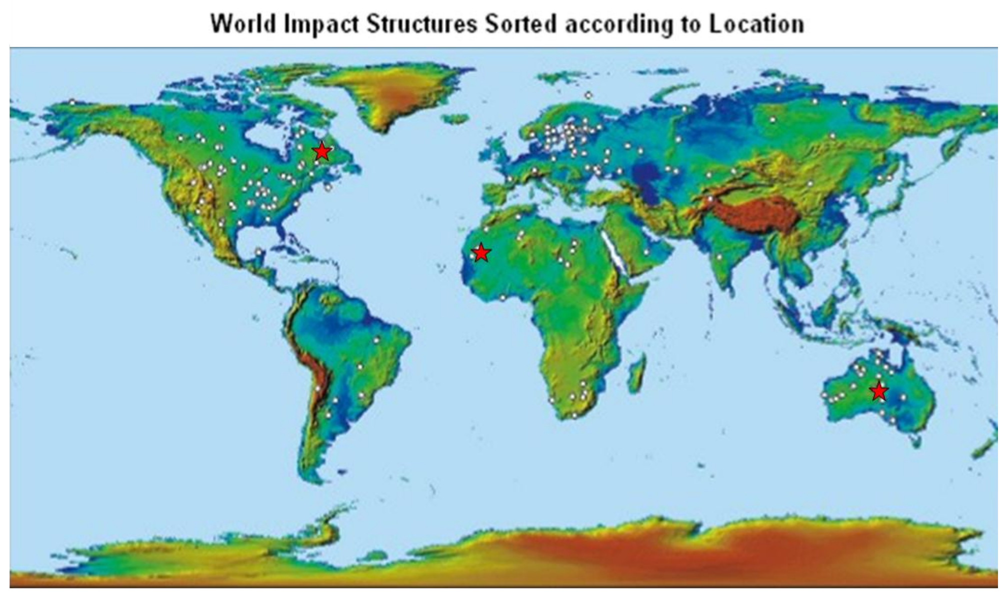


Image Credit: Earth Impact Database: http://www.unb.ca/passc/ImpactDatabase/CILocSort.html

★ = craters observed

IMAGE ILLUSTRATIONS

To help you illustrate your observations so readers of your research have a better understanding of your observations, image illustrations can be very powerful. See the two image illustration examples below.

IMAGE ILLUSTRATION #1: BARELY VISIBLE RIMS

Image Illustration #1: Most craters on Earth appear to be extremely modified (eroded) or destroyed. Rims like the one shown in the image above are oftentimes barely visible. (ISS028-E-14782: Shoemaker Crater)

IMAGE ILLUSTRATION #2: CRATER MODIFICATION

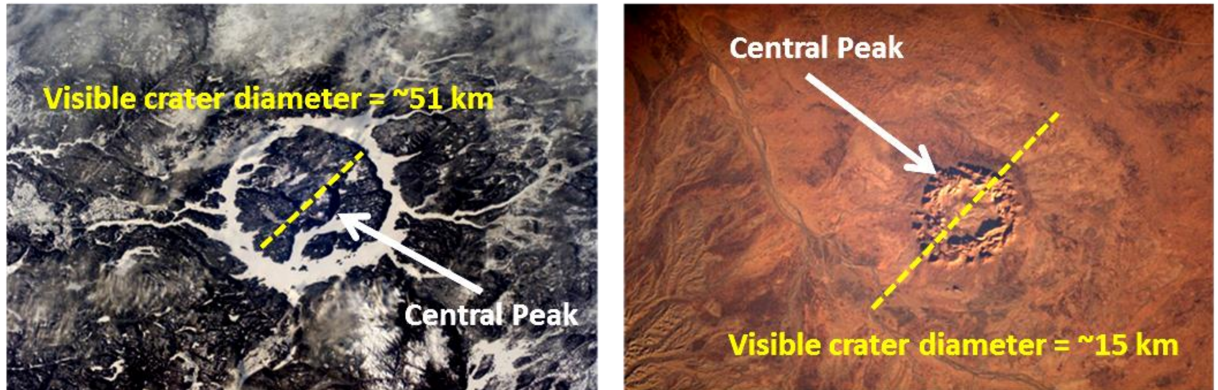


Image Illustration #2: Craters on Earth are modified by wind, water, ice, or volcanic processes. Oftentimes this modification makes it difficult to detect a central peak (if one exists). Additionally, the visible extent of the crater diameter may different from crater diameters indicated in the Earth Impact Database. For example, Manicouagan is listed as having a diameter of 85 km (~51 km shown here) and Gosses Bluff is listed as having a diameter of 22 km (~15 km shown here).

IMAGE ILLUSTRATION #1:

Observation #1: The rim of this crater is "broken".

Observation #2: This crater is being modified by different processes, including water erosion.

Observation #3: The crater in this image appears to be destroyed with hardly any visible detection of a wall, rim, or ejecta.

IMAGE ILLUSTRATION #2:

Observation #1: Central peaks in these images are very difficult to identify.

Observation #2: The terrain/environment of these two impact craters appear to be very different.

Observation #3: The original crater diameters (retrieved from the Earth Impact Database) are larger than the crater diameter measured using the measurement reference lines provided with each image. Manicouagan has a current measured diameter of ~51km; diameter of Gosses Bluff is ~15km.

PROCESS OF SCIENCE STEP 7: Analyze & Interpret Data

Once you display your data and have listed observations of those data displays, you are ready to do one of the most important steps of your research – analyze and interpret the data. Analysis and interpretation of data are done by thinking about how specific observations and knowledge you have directly relate to your question. Your goal is to be able to draw conclusions about your research with supporting evidence.

As you analyze your data, focus on your research question and hypothesis/es.

Research Question: What are the similarities and differences between the characteristics of craters on different planetary worlds? What might these characteristics reveal about the geologic history of those worlds compared to Earth?

Hypothesis: *[This should be the original set of hypothesis statements you made earlier.]*

- Earth craters will be *smaller, larger, or the same size* compared to craters on other planetary worlds.
- Earth craters will more often *have or not have* a central peak compared to craters on other planetary worlds.
- Earth craters will have a *more or less* defined rim compared to craters on other planetary worlds.
- Earth craters will have *smoother or more terraced* walls compared to craters on other planetary worlds.
- Earth craters will more often be *preserved, modified, or destroyed* compared to craters on other worlds.
- Earth craters will *more often or less often* have visible ejecta blankets compared to craters on other worlds.

As part of Step 7, each group should fill out the *Analysis and Interpretation of Data* table for the planetary world you observed. As you analyze and interpret data, focus on: 1) Specific/listed observations from Data Displays; 2) Interpretation of what those observations mean with respect to your question/hypotheses; and 3) Evidence that support your interpretations.

Consider including information that focuses on each observation category you logged on your data tables. For example, you made observations of the following characteristics: 1) crater classification; 2) central peaks; 3) crater diameter; 4) rim definition; 5) crater walls; and 6) visible ejecta. You should be able to use the information you displayed, observed, and analyzed to draw conclusions about what these overall characteristics reveal about the geologic history of these other worlds compared to Earth.

The table on the next page provides starting information on two of these categories: c*rater classification* and c*entral peaks*. Your finished table should reflect your overall analysis and interpretation of data, related to each category, for whichever planetary world you observed. As you look at the sample table, notice how the information listed in column 1 is an observation directly from Step 6 (the specific data display and observation are listed in parenthesis). As you complete this step, you should revisit your data displays and listed observations and look for specific observations that are especially relevant to your research. As previously mentioned, observations are very important in that they basically state patterns or notable information illustrated in a

data display. In Step 7, as you think about how those observations apply to your research, you are analyzing and interpreting the data. Your interpretation (column 2) of a listed observation compared to someone else's interpretation can vary. This is why it is important to have supporting evidence (column 3) to back up your interpretations. This will also help as you draw conclusions.

In Step 7 you will: 1) Fill out an *Analysis and Interpretation of Data* table; and 2) Share your analysis with the class.

Sample table focusing on data collected from Earth craters. This same table structure would be used for *each* planetary world:

ANALYSIS AND INTERPRETATION OF DATA **Planetary World: EARTH**		
Specific Observation from Data Display	**Interpretation(s) of What Observation Means with Respect to Your Question and/or Hypothesis**	**Evidence That Supports Your Interpretation** (from specific data displays and/or background knowledge)
IMPORTANT: Be sure to list a relevant observation you listed with one of your data displays.	*IMPORTANT: Describe how this observation can be interpreted – what does it reveal about the age of the planetary surface or the processes affecting the surface.*	*IMPORTANT: Provide additional evidence that supports your interpretation. Did you illustrate this point in another data display; did you read something about this in the text provided or somewhere else?*
1. CRATER CLASSIFICATION: Example: This crater is being modified by different processes, including water erosion. (Image Illustration #1, Observation# 2)	Example: Impact craters on Earth are mostly modified and are therefore middle-aged to old. This allows us to infer that the Earth has not been impacted by any significant object recently and there are active processes currently modifying these craters.	Example: Earth has current and active weathering and erosion processes that continually modify/shape the surface of the planet.
2. CENTRAL PEAKS: Example: Craters with a diameter over 15 km appear to have a central uplift/peak. (Earth Data Table, Observation #3)	Example: The majority of impact craters on Earth do not have central peaks. Large craters on Earth may have had visible central peaks, but if they did, they have been since eroded; Earth has more visible small simple craters than complex craters. Older complex crater may have been eroded and "erased" due to weathering and erosion.	Example: Most visible craters on Earth are simple craters and are much smaller than those observed on other planetary worlds. (See Earth Graph #1). Older more complex craters have been nearly destroyed (Image Illustrations #1 & 2). This is likely due to active weathering & erosion.
3. CRATER DIAMETER…		
4. RIM DEFINITION…		
5. CRATER WALLS…		
6. VISIBLE EJECTA …		

Fill out this *Analysis and Interpretation of Data Table* for the planetary world you investigated. (Use additional paper, as necessary.)

ANALYSIS AND INTERPRETATION OF DATA: **Planetary World: ___________________________**		
Specific Observation from Data Display	**Interpretation(s) of What Observation Means with Respect to Your Question and/or Hypothesis**	**Evidence That Supports Your Interpretation** (from specific data displays and/or background knowledge)

SHARING YOUR ANALYSIS:

Be prepared to share information you have included in you *Analysis and Interpretation of Data* table. As you present your information: 1) Be prepared to discuss your information related to all 6 crater characteristics, 2) Be prepared to show any related data displays that allow you to illustrate your specific observations and help support your interpretations, and 3) Be prepared to discuss any limitations related to your research (not enough data, needed more area to be shown in images, something else?).

As you listen to each group's presentation, be prepared to contribute additional information as you see fit. In the table below, fill in the names of the planetary worlds you have investigated. Take notes so you can later draw conclusions about this research.

SUMMARY TABLE (use additional paper, as necessary)

	Earth	____________	____________	____________
Crater Classifica-tion				
Central Peaks				
Crater Diameter				
Rim Definition				
Crater Walls				
Visible Ejecta				
Other Notes or Limitations				

PROCESS OF SCIENCE STEP 8: Draw Conclusions

Now that you have completed all the above steps, you are now ready to draw conclusions about your question and hypothesis. This is an essential part of your investigation as it allows you to synthesize your overall research and state your results. It also allows others to expand or build on your research in the future.

1**. RESEARCH QUESTION:** What are the similarities and differences between the characteristics of craters on different planetary worlds? What might these characteristics reveal about the geologic history of those worlds compared to Earth? (*Suggestion: You may consider framing your answer to include whether a studied planetary world has an "older" or "younger" surface compared to Earth (or each other) based on the characteristics of craters you observed. What does your investigation tell you about the current or past processes affecting those worlds?)*

Based on your research and analysis of data, what do you think is the answer to your question? Be sure to summarize supporting evidence.

2. **HYPOTHESIS:** Based on your research and analysis of data, indicate whether each of you hypotheses were supported or refuted? Summarize pertinent evidence.

HYPOTHESIS (Circle the choice that indicates your original hypothesis)	**Supported or Refuted**
Earth craters will be *smaller, larger, or the same size* compared to craters on other planetary worlds.	
Earth craters will more often *have or not have* a central peak compared to craters on other planetary worlds.	
Earth craters will have a *more or less* defined rim compared to craters on other planetary worlds.	
Earth craters will have *smoother or more terraced* walls compared to craters on other planetary worlds.	
Earth craters will more often be *persevered, modified, or destroyed* compared to craters on other worlds.	
Earth craters will *more often or less often* have visible ejecta blankets compared to craters on other worlds.	

Include a summary of pertinent evidence:

WHAT DOES IT ALL MEAN?

As part of any research investigation, it is important to think about the bigger picture. What are the potential implications of this research, why is it important, and what does it all mean? The research you have conducted provides you with useful information related to one of the most dominant processes within our Solar System – the impact process. As you have learned, there are chunks of rock or ice (comets and fragments of asteroids or planets) that have impacted planetary surfaces (including Earth) in our Solar System throughout history. Along with the use of geologic principles, scientists are able to use specialized dating techniques that allow them to examine rocks in areas impacted to determine actual ages of craters on Earth. For example, one of the youngest craters on Earth is Barringer Crater in Arizona. This simple crater is ~50,000 years old and is ~1.2 km in diameter. One of the oldest craters on Earth is the Vredefort crater in South Africa. This complex crater is over 2 billion years old and is ~160 km in diameter. While we are currently unable to visit other worlds to determine actual ages of planetary craters, crater classification and crater density allow us to infer the relative ages of craters and planetary surfaces. Additionally, the modification of craters reveals the geological and/or other processes that have shaped the surfaces of planetary worlds.

By conducting this investigation on impact craters, you should now be able to apply what you have learned to the "bigger picture". You should be able to 1) reflect on and better understand the history of our Solar System, 2) make predictions about potential future impacts, and 3) consider future robotic or even human exploration of other worlds.

Based on your investigation, discuss the answers to the following questions. Make additional observations as necessary:

1. Which are older: large complex craters or small simple craters? What does that tell you about the size of materials that may be have impacted planetary worlds early in the history of the Solar System versus the size of materials that have more recently impact surfaces? Explain your answer.

2. If the Earth or other planetary worlds were impacted by an object in the future, do you think this object would likely be relatively large or small? Explain your answer.

3. NASA plans to send astronauts to visit another planetary world in the future to help us better understand our Solar System. If you had the opportunity to choose which planetary world to visit, which would you choose and why?